DSN G/T_{op} and Telecommunications System Performance

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This article provides an intersystem comparison of present and evolving DSN microwave receiving systems. Comparisons of the receiving systems are based on the widely used G/T_{op} *figure of merit, which is defined as antenna gain divided by operating system noise temperature. In 10 years, it is expected that the DSN 32-GHz microwave receiving system will improve the* G/T_{op} *performance over the current 8.4-GHz system by 8.3 dB. To compare future telemmunications system end-to-end performance, both the receiving systems'* G/T_{op} *and spacecraft transmit parameters are used. Improving the 32-GHz spacecraft transmitter system is shown to increase the end-to-end telecommunications system performance an additional 3.2 dB, for a net improvement of 11.5 dB. These values are without a planet in the field of view (FOV). A Saturn mission is used for an example calculation to indicate the degradation in performance with a planet in the FOV.*

I. Introduction

The ground-based microwave receiving system is an important and continuously evolving element of the DSN spacecraft-to-ground telecommunications system. The recent development of a research and development (R&D) 34-m beam waveguide (BWG)[1] antenna is part of a plan to prepare for DSN operation at Ka-band (the Ka-band deep space-to-ground frequency allocation is 31.8 to 32.3 GHz). This article provides an intersystem comparison based on the receiving system figure of merit, G/T_{op} (defined as antenna gain divided by operating system noise temperature), and the spacecraft transmitter power and antenna area. These parameters are used with an end-to-end telecommunications system performance (TSP) equation, which is defined below. The comparisons represent current understanding of DSN antennas and low noise amplifiers.

The receiving system figure of merit, G/T_{op}, is determined by parameters that can be measured conveniently and separately. Throughout this article, G/T_{op} characterizes the receiving microwave antenna and receiver front-end; that is, cosmic noise, atmospheric effects, antenna, maser, and the follow-up amplifier.

The microwave receiving system figure of merit is [1]

$$M = G/T_{op} \tag{1}$$

[1] M. Britcliffe, L. S. Alvarez, D. A. Bathker, P. W. Cramer, T. Y. Otoshi, D. J. Rochblatt, B. L. Seidel, S. D. Slobin, S. R. Stewart, W. Veruttipong, and G. E. Wood, *DSS-13 Beam Waveguide Antenna Project*, JPL D-8451 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 15, 1991.

where

$$M = G/T_{op} = \text{receiving system figure of merit}$$

$$M\ (\text{dB}) = G\ (\text{dB}) - T_{op}\ (\text{dB})$$

$$G = \text{antenna gain (relative to isotropic), ratio}$$

$$G\ (\text{dB}) = 10 \log G$$

T_{op} = receiving system operating noise temperature, K

$$T_{op}\ (\text{dB}) = 10 \log T_{op}\ (\text{relative to } T_{op} = 1\ \text{K})$$

In 1960, DSN 26-m antennas with 30-percent efficiency at 960 MHz and 1500-K receivers had a figure of merit, G/T_{op}, of 11 dB [2, pp. 2–15]. This was increased to 36 dB at 2.3 GHz in 1965. For the 1980 Voyager–Saturn encounter, DSN 64-m antennas had achieved an efficiency of 50 percent at 8.4 GHz and a G/T_{op} of 58 dB. Since antenna gain G is proportional to the product of effective antenna area and frequency squared, much of the improvement in G/T_{op} is obtained by increasing the operating frequency. Further improvements are obtained by increasing the antenna area and efficiency and by lowering the receiving system noise temperature. The benefit of higher frequencies is limited by technical difficulties such as more stringent antenna surface and pointing tolerances, low-noise amplifier complexity, and, in particular, increased atmospheric losses.

Present DSN 70-m antennas with 69-percent efficiency and microwave receivers at 8.4 GHz achieve a G/T_{op} of 60.4 dB. This is expected to be improved to 68.7 dB in 10 years at 32 GHz; this does not include a planet in the field of view (FOV). The 32-GHz-receiving-antenna estimates in this article apply to individual antennas located at Goldstone, at a 30-deg elevation angle with 90-percent weather confidence. Many future missions to the outer planets are planned as orbiters, some with landers. Therefore, the effects of a planet in the DSN antenna's FOV are important. Saturn is used throughout this article as an example of a planet in the FOV.

The noise temperature contribution of Saturn to T_{op} is estimated at 1.7 and 18 K for the 70-m antenna at 8.4 and 32 GHz, respectively. G/T_{op} alone can be used to compare the TSP of systems, assuming the same transmitter antenna effective area, transmitter power, and modulation/coding performance. G/T_{op} alone is not sufficient, however, when comparing systems with different spacecraft transmitter parameters. A telecommunication system performance ratio ($TSPr$) equation is given in this article to compare future microwave and higher frequency end-to-end systems with the current DSN microwave systems. This article describes present and future deep space TSP estimates for X-band (8.4 GHz) and Ka-band (32 GHz) in the DSN. This follows earlier DSN articles [3] and studies [4].

II. Microwave Receiving System Figure of Merit

In a microwave deep space receiving system, thermal noise is usually the dominant source of noise that limits the system performance. In terms of the receiving system output noise power, the receiving system operating noise temperature is given by [5, p. 7-1]

$$T_{op} = No/kBG \tag{2}$$

where

No = output thermal noise power of receiving system, W

k = Boltzmann's constant, 1.381×10^{-23} J/K

B = bandwidth, Hz

G = receiver gain, ratio

The receiving system operating noise temperature[2] is defined at the receiving system input [7]

$$T_{op} = Ta + Te \tag{3}$$

where

Ta = effective noise temperature of the antenna, K

Te = effective noise temperature of the receiver, K

The primary noise temperature contributions for the DSN microwave receiving systems are given in Tables 1

[2] A high-frequency correction [6] $Tc = -0.024f\ (\text{GHz}) + 0.000192f\ (\text{GHz})^2/T + \cdots$ is required for the system thermal noise temperature. This is applied in the noise temperature tables of this article as a reduction of the 2.76-K cosmic background noise. For the microwave parameters in this article, the second term is less than 0.02 K. Therefore, only the first term (0.2 and 0.8 K for 8.4 and 32 GHz, respectively), which is independent of T, is used in this article. Further reduction in the cosmic background temperature defined at the receiver input occurs due to atmospheric attenuation. Quantum noise, $Tq = hf/k = 0.0480f\ (\text{GHz}) = 0.40$ and 1.54 K at 8.4 and 32 GHz, respectively, is included as part of the system noise temperature in these tables.

and 2 for 8.4 and 32 GHz, respectively. The 8.4-GHz systems are operational in the DSN. The 32-GHz low-noise receiver and antenna components have been tested in R&D laboratory and field configurations to provide achievable performance estimates.

The noise temperature contribution of the troposphere is defined for an antenna elevation angle of 30 deg and 90-percent weather confidence for Goldstone.[3] At X-band and above, water vapor, precipitation, and clouds cause increased atmospheric attenuation and noise temperature.

Weather confidence is the percentage of time that the predicted TSP is equaled or exceeded due to weather effects only. Equivalently, weather confidence is equal to 100 percent minus the percentage of time the link performance is degraded below the predicted value.

Present DSN antennas use room temperature feed components and 4.5-K physical cryogenically cooled maser amplifiers on the tipping structure of the antenna, where space and accessibility are limited. In the future, primary improvements will occur with use of BWG antennas that facilitate the use of cryogenic cooling for waveguide and feed components below 20 K and maser amplifiers to 1.7 K physical, with resultant lower noise-temperature receiving systems. Combined with antenna gain values, these results are shown in Tables 3 and 4 for G/T_{op} estimates of DSN microwave 34-m and 70-m antennas operating at 8.4 and 32 GHz, now and in the future. Microwave components for the 32-GHz systems have been developed, and preliminary measurements provide data for the estimates shown in Table 4.

As shown in Table 3, the present G/T_{op} performance of 60.1 dB and 60.4 dB (with and without Saturn in the FOV) for the Goldstone 70-m antenna at 8.4 GHz, 30-deg elevation angle, and 90-percent weather confidence is used as a baseline for this study.

Antenna efficiency improvements are planned to maximize the 32-GHz antenna gain, in addition to 8.4- and 32-GHz noise temperature reductions. Table 4 shows 68.7 dB is predicted as the best microwave G/T_{op} value. This is achieved at 32 GHz on a DSN 70-m BWG antenna with the feed and waveguide components cooled to 20 K and the maser to 1.7 K physical. This represents an 8.3-dB improvement relative to the present baseline performance of 60.4 dB at 8.4 GHz.

The first deep space test application of 32 GHz will use DSS 13 and the Mars Observer (MO) spacecraft with the Ka-band link experiment (KABLE).[4] MO will have a simultaneous 8.4- and 33.7-GHz transmit capability. This provides an opportunity to verify the end-to-end Ka-band telemetry system performance by direct comparison with X-band.

III. Telecommunication System Performance

The Friis free-space received-power transmission formula [8] is manipulated and expanded to a form useful for computing comparison ratios of one telecommunication system relative to another

$$TSPr = Pr \times ATr \times Mr \qquad (4)$$

where

$TSPr$ = telecommunication system performance comparison ratio

$TSPr\ (\text{dB}) = Pr\ (\text{dB}) + ATr\ (\text{dB}) + Mr\ (\text{dB})$

Pr = transmitter power comparison ratio

$Pr\ (\text{dB}) = 10 \log Pr$

ATr = transmitter antenna effective area comparison ratio

$ATr\ (\text{dB}) = 10 \log ATr$

Mr = receiving system figure of merit G/T_{op} comparison ratio

$Mr\ (\text{dB}) = 10 \log Mr$

The form of the power transmission formula used in Eq. (4) is useful for a transmitter with a size-limited antenna [9]. For most of this article, microwave spacecraft transmitter power and antenna area (and efficiency) are assumed unchanged with frequency, that is, $Pr \times ATr = 1$. For this assumption, Eq. (4) shows that the system figure of merit ratio, $Mr = (G/T_{op})r$, is a useful and convenient measure for comparing relative performances.

[3] S. Slobin, "DSN Telecommunications Interfaces, Atmospheric and Environmental Effects," TCI 40, Rev. C (internal document), to be published in *DSN/Flight Project Interface Design Document*, JPL 810-5, Rev. D, Jet Propulsion Laboratory, Pasadena, California, 1992.

[4] S. Butman and J. Meeker, *DSN Advanced Systems—Mars Observer Ka Band Link Experiment Plan*, JPL D-8799 (internal document), Jet Propulsion Laboratory, Pasadena, California, August 1991.

The reference telecommunications system for this article is the Voyager spacecraft's 8.4-GHz transmitting microwave system and the DSN Goldstone 70-m receiving station. The Voyager spacecraft has a 3.7-m-diameter antenna and approximately 20-W X-band transmitter output power. The antenna has 62-percent area efficiency, about 0.6-deg half-power beamwidth, and a pointing accuracy of about 0.1 deg.

An exception to the use of the reference system is included as an example where $Pr \times ATr \neq 1$, emphasizing the need to compare the end-to-end TSP. Future use of higher frequencies with millimeter and optical wavelengths for deep space communications is expected to allow the use of smaller spacecraft transmitting antennas with less transmitter power. A future study summarizing and comparing the performance of higher frequency systems with the current microwave systems is planned.

For this article, the example where $Pr \times ATr \neq 1$ assumes a 32-GHz spacecraft transmitting system with a shaped, clear aperture, BWG antenna, and a high-efficiency 30-W transmitter (see Table 5). The antenna diameter is 3.7 m, but the effective antenna area is 1.4 times greater (+1.4 dB) than the reference system because the area efficiency is 86 percent. The 30-W transmitter provides 50 percent more power (+1.8 dB) than the reference system, and $Pr \times ATr = 2.1$ (+3.2 dB).

Table 5 shows an estimated 8.3-dB-improved TSP in 10 years for ground-based, 32-GHz microwave systems compared with the DSN Goldstone 8.4-GHz 70-m antenna's present 60.4-dB G/T_{op} performance. A 1988 study gives similar results.[5] For the portion of the study where $Pr \times ATr = 1$ (no transmitter improvements), $TSPr$ is determined by the relative figure of merit, Mr.

IV. Tolerances

The values in the text and tables do not indicate tolerances. The DSN receiving stations' X-band G/T_{op} tolerance is ±0.4 dB. The TSP at 30-deg antenna elevation angle and 90-percent weather confidence is estimated as ±0.6 dB. The 32-GHz G/T_{op} tolerance uncertainties are much worse than the 8.4-GHz tolerances because weather effects dominate the ground station performance, and there is no deep space experience to verify existing models. A ±2-dB tolerance is estimated for 32-GHz end-to-end performance. A precision of 0.1 dB was included in the text and tables to avoid accumulation of round-off errors; this does not imply accuracy to 0.1 dB.

[5] J. W. Layland, R. C. Clauss, R. L. Horttor, D. J. Mudgway, R. J. Wallace, and J. H. Wilcher, *Ka-band Study—1988, Final Report*, JPL D-6015 (internal document), Jet Propulsion Laboratory, Pasadena, California, February 15, 1989.

V. Conclusion and Future Directions

The data presented for the DSN ground system point to significantly improved figure of merit and telecommunications system performance in the coming years. Increasing the operating frequency from the present 8.4 GHz to 32 GHz is expected to result in a net gain of 8.3 dB (without significant planet noise) and 7.0 dB (with Saturn in the FOV) in the next 10 years, relative to the current DSN Goldstone 70-m antenna.

Use of a high-efficiency 32-GHz spacecraft transmit system can increase telecommunications system performance another 3.2 dB, increasing the net performance gain from 8.3 to 11.5 dB without a planet in the FOV.

The potential improvements for the 32-GHz systems are important for future deep space communications. These improvements could provide telecommunication systems with higher data rates for the spacecraft-to-Earth link and/or some combination of lower transmitter power, smaller antenna size, and lower weight. The choice of which improvements to use, and when, will depend upon practical considerations that include technical readiness and cost.

Future options for performance improvements in DSN telecommunications systems during the time beyond 2001 include:

(1) Higher receiving-station antenna gain resulting from increased antenna-aperture areas, probably using arrays. Lower system-noise temperature using antenna BWG technology with super-cooled, low-noise maser amplifiers and cooled waveguide components.

(2) Use of wavelengths/frequencies that better optimize the combination of receiving station G/T_{op}, spacecraft transmitter power, spacecraft antenna size, and receiver performance according to constraints affecting deep space missions.

(3) Improved spacecraft transmitter components, resulting in higher antenna efficiencies and power.

Future use of Earth-orbiting deep space relay satellites will provide a major change for the space-to-ground telecommunications system. This architecture eliminates tropospheric loss and noise and potentially allows greatly increased data rates for telemetry.

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[2] N. A. Renzetti, C. T. Stelzried, G. K. Noreen, S. D. Slobin, S. M. Petty, D. L. Trowbridge, H. Donnelly, P. W. Kinman, J. W. Armstrong, N. A. Burow, M. K. Tam, J. W. Layland, and A. L. Berman, *The Deep Space Network—A Radio Communications Instrument for Deep Space Exploration*, JPL Publication 82-104, Jet Propulsion Laboratory, Pasadena, California, July 15, 1983.

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[5] C. Stelzried, *The Deep Space Network—Noise Temperature Concepts, Measurements, and Performance*, JPL Publication 82-33, Jet Propulsion Laboratory, Pasadena, California, September 15, 1982.

[6] M. Viggh, "How Noisy Is That Load," *Microwaves*, vol. 15, no. 1, pp. 54, 56, January 1976.

[7] "IRE Standards on Electron Tubes: Definitions of Terms, 1962 (62 IRE 7.S2)," *Proceedings of the IEEE*, pp. 434–442, March 1963.

[8] H. T. Friis, "A Note on a Simple Transmission Formula," *Proceedings of the IRE*, pp. 254–256, 1946.

[9] K. W. Linnes, W. D. Merrick, and R. Stevens, "Ground Antenna for Space Communication System," *IRE Transactions on Space Electronics and Telemetry*, p. 45, March 1960.

Table 1. DSN receiving systems' noise temperature performance at 8.4 GHz, K.

Configuration	Antenna noise temperature contributions, K							Maser[b] Te, K	Total T_{op}, K	
	Cosmic background[a]	Atmosphere	Antenna	BWG	Dichroic plate	Feed and WG	Ta, K			SFOV[c]
Now[c,d]	2.6	5.2	4.3	0	1.2	6	19.3	4	23.3	25.0
10 years[c,e]	2.6	5.2	4.3	1	1.2	0.3	14.6	1	15.6	17.3

Conditions: 30-deg antenna elevation angle and Goldstone, California, 90-percent weather confidence.

[a] Includes high-frequency thermal noise temperature correction, Tc.

[b] Includes quantum noise temperature, Tq, and noise contribution from the follow-on amplifiers.

[c] Saturn in the field of view (SFOV) adds about 1.7 K to T_{op} at 8.4 GHz.

[d] Non-BWG, uncooled feed, maser at 4.5 K, physical temperature.

[e] BWG, feed cooled, maser at 1.7 K, physical temperature.

Table 2. DSN receiving systems' estimated noise temperature performance at 32 GHz, K.

Configuration	Antenna noise temperature contributions, K							Maser[b] Te, K	Total T_{op}, K	
	Cosmic background[a]	Atmosphere	Antenna	BWG	Dichroic plate	Feed and WG	Ta, K			SFOV[c]
Now[c,d]	1.8	25.4	5	0	3	7	42.2	11	53.2	71.2
10 years[c,e]	1.8	25.4	5	1.7	2	0.5	36.4	4	40.4	58.4

Conditions: 30-deg antenna elevation angle and Goldstone, California, 90-percent weather confidence.

[a] Includes high-frequency thermal noise temperature correction, Tc.

[b] Includes quantum noise temperature, T_q, and noise condition from the follow-on amplifiers.

[c] SFOV adds 18 K to T_{op} at 32 GHz.

[d] Achievable for R&D configuration non-BWG, uncooled feed, maser at 4.5 K, physical temperature.

[e] BWG, feed cooled, maser at 1.7 K, physical temperature.

Table 3. DSN 8.4-GHz receiving antennas' G/T_{op} performance.

Configuration	Diam., m	Antenna gain, dB	T_{op}, K	G/T_{op}, dB	
					SFOV[a]
Now	34	68.2	23.3	54.5	
10 years	34	68.5	15.6	56.5	
Now	70	74.1	23.3	60.4[b]	60.1[b]
10 years	70	74.7	15.6	62.8	62.4

Conditions: 30-deg antenna elevation angle and Goldstone, California, 90-percent weather confidence, resulting in 0.08-dB atmospheric loss.

Ten-year improvements: BWG with cooled feeds and masers cooled to 1.7 K, physical temperature.

[a] Saturn in the field of view (SFOV).

[b] Baseline performances.

Table 4. DSN 32-GHz receiving antennas' G/T_{op} performance.

Configuration	Diam., m	Antenna gain, dB	T_{op}, K	G/T_{op}, dB	
					SFOV[a]
Now	34	77.2	53.2	60.0	
10 years	34	79.2	40.4	63.1	
Now	70	82.4	53.2	65.2	63.9
10 years	70	84.8	40.4	68.7	67.1

Conditions: 30-deg antenna elevation angle and Goldstone, California, 90-percent weather confidence, resulting in 0.42-dB atmospheric loss.

Now: Achievable based on DSS-13 R&D 34-m antenna gain measurements and Table 2 noise temperature estimates.

Ten-year improvements: Antenna gains, BWG with cooled feeds, and masers at 1.7 K, physical temperature.

[a] Saturn in the field of view (SFOV).

Table 5. DSN 10-year future microwave TSP comparison, decibels relative to present 70-m antenna at 8.4 GHz with 60.4-dB figure of merit, G/T_{op} without SFOV and 60.1 dB with SFOV.

Parameter ratio	8.4 GHz			32 GHz			32-GHz HE spacecraft TS		
	34 m	70 m	70-m, SFOV[a]	34 m	70 m	70-m, SFOV[a]	34 m	70 m	70-m, SFOV[a]
PrATr (transmitter power × antenna area)	0	0	0	0	0	0	3.2	3.2	3.2
Mr (receiving system figure of merit)	−3.9	2.4	2.3	2.7	8.3	7.0	2.7	8.3	7.0
TSPr (telecommunications system performance)	−3.9	2.4	2.3	2.7	8.3	7.0	5.9	11.5	10.2

Conditions:

Transmitter: Same power and antenna efficiencies except for 32-GHz high-efficiency spacecraft transmit system (HE spacecraft TS) with 3.7-m antenna diameter.

Receiving: 30-deg antenna elevation angle and Goldstone, California, 90-percent weather confidence.

[a] Saturn in the field of view (SFOV).